HYPERSPECTRAL INFRARED SOUNDING FOR IMPROVING WEATHER PREDICTION ON MARS.

M.A. Mischna[1], T. Pagano[1], G. Liuzzi[2], O. Reale[2,4], T. Fauchez[2,4], S. Desouza-Machado[3], G. Martínez[4], G. Asrar[4], C. Barnet[5], [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr. Pasadena, CA, 91109, michael.a.mischna@jpl.nasa.gov, [2]NASA Goddard Space Flight Center, [3]University of Maryland, Baltimore County, [4]Universities Space Research Association, [5]Science and Technology Corporation

Introduction: Knowledge of temperature is a key element in characterization of a planetary atmosphere—it can be used directly to calculate atmospheric density and, indirectly, to provide information about atmospheric winds. Atmospheric temperature observations also make it possible to improve and validate global climate models (GCMs), which are widely used both for scientific studies and support for robotic missions to planetary surfaces. Numerical models like GCMs are the primary workhorses with which global atmospheric studies are performed today, but they increasingly rely on the availability of atmospheric data either for model validation—to assess the accuracy of the existing GCM for its intended uses—or to improve the model accuracy by using, for example, data assimilation approaches, e.g., [1-4].

We have determined that a nadir-viewing, cross-track scanning, hyperspectral infrared sounder (HSIR) can provide information about the martian boundary layer—the lowest ~10 km of the atmosphere, a region that has heretofore been poorly observed due to the limitations of prior orbital instruments. Hyperspectral IR sounders are widely used today for measuring temperature and water vapor profiles on Earth's atmosphere with high impact to the operational forecast [5]. While we choose to focus on the application of HSIR to the martian atmosphere, we note that an instrument of this type would be equally capable of making advances in studies of Venus' CO_2 atmosphere as part of any future combined effort of observations and modeling as described below. State-of-the-art infrared detector technology now allows megapixel formats that enable a larger collecting area for the detector, allowing the optical system to be smaller. These advancements have led to the ability to achieve HSIR capabilities at Mars, similar to those provided in today's Earth observing sensors, in the size of a CubeSat.

Instrument Observations of the Martian Atmosphere: We have a broad knowledge of Mars' CO_2 atmosphere from a combination of direct observation and extensive numerical modeling efforts. Regular observations of the martian atmosphere have been conducted from a fleet of orbiting spacecraft, nearly continuously, for the past 25 years, with additional observations from Mariner 9 and the Viking Orbiters in the 1970s, and the Phobos-2 spacecraft in the 1980s. The Thermal Emission Spectrometer (TES) on board the Mars Global Surveyor and the Mars Climate Sounder (MCS) on board the Mars Reconnaissance Orbiter have provided regular global coverage of the martian atmosphere, nearly continuously since 1997, by profiling the atmosphere using emission from the 15 μm CO_2 band. The Planetary Fourier Spectrometer (PFS) on board ESA's Mars Express spacecraft has also provided additional profiling capabilities in this band. Together, these three instruments have provided us with much of our current understanding of the 4-D structure of the martian atmosphere and are benchmarks against which we will compare the capabilities of HSIR.

Numerical Models of the Martian Atmosphere: GCMs of the martian atmosphere ([6-8], among others) are widely used to simulate atmospheric conditions at times, and locations, where observations are lacking. These GCMs are based on terrestrial models, but adapted to martian conditions (including gravity, atmospheric composition, etc.), and 'tuned' to provide a best fit to available historical observations.

Recently, efforts have been underway to assimilate Mars observational data into these climate models, in essence, by using spacecraft data at known locations and times to 'steer' the model output, either through analysis correction, e.g., [3,9] or ensemble-based approaches, e.g., [1,2], towards a 'true' state. Assimilation can work efficiently when the data and models are in synchrony with each other; model resolution should approximately match the resolution of the data, and data should be available at many times of day and in many locations. With too few data (such is the present state), the model is not globally steered towards the best solution, and large 'bins' of data (either in space or time) must often be averaged before their assimilation into the model [1].

Today, Mars GCMs are commonly run with 40 or more vertical atmospheric layers, making the situation even more imbalanced, particularly in the atmospheric boundary layer, where temperatures are directly affected by the martian surface. For a GCM with 5° horizontal resolution, and with today's measurements, only one out of every six model grid points may have an associated observation(s) available to assimilate. At more current Mars GCM horizontal resolutions of 1-2°, then, there can be gaps as large as 15-30 grid points between adjacent observation tracks.

The Value of HSIR: HSIR can markedly increase the vertical and horizontal resolution of retrieved temperature profiles in the near-surface boundary layer of the martian atmosphere. A cross-track scanning HSIR accomplishes this by operating along the 4.3 µm (shortwave) and/or 15 µm (longwave) CO_2 absorption bands, with spectral resolution ($\lambda/\Delta\lambda > 1000$) at ~10-km-scale horizontal resolution. Due to its hyperspectral approach, HSIR can obtain up to 2-3 km vertical resolution—a factor of two greater than the current state-of-the-art. By scanning the surface in the cross-track direction, HSIR is capable of retrieving radiance information at a scale more consistent with today's numerical models, providing assimilation data to the models over broader swaths than before. A single HSIR instrument can provide over 180 soundings in a single 23 s scan vs. 1 sounding in a 34 s scan for MCS. Additional instruments comprising a spacecraft constellation can improve time coverage and provide additional information on winds through data assimilation, or through atmospheric motion vector (AMV) tracking [10].

HSIR Instrumentation: New technologies exist today that greatly reduce the size, weight and power (SWaP) of an HSIR instrument in both wavelength bands. For example, JPL's CubeSat Infrared Atmospheric Sounder (CIRAS) [11], for Earth-based applications, achieves spectral coverage from 4.08-5.13 µm, with spectral resolution of 3.3 nm. This instrument provides over 625 spectral channels and fits in a 4U volume. JPL has completed ambient testing of a high-fidelity prototype of CIRAS, bringing it to TRL 4, with plans to achieve TRL 6 by the end of 2021. We can leverage this development towards applications to shortwave IR profiling of planetary atmospheres. Achieving comparable performance in the LWIR CO_2 band (at 15 µm) would be possible in a SmallSat, though it requires more power than the shortwave band.

Radiative Transfer Simulations and Retrievals: Simulations of sample HSIR spectra and a characterization of its sensitivity to the atmospheric state have been performed. The simulations were made with the Planetary Spectrum Generator (PSG, [12]) which includes a retrieval module capable of computing the sensitivity of simulated data to specified parameters in the form of averaging kernels and Degrees of Freedom of Signal (DOFS) for the instruments being considered. Instrument characteristics (noise and spectral response) for an HSIR grating sounder similar to CIRAS operating in the shortwave CO_2 band and a notional instrument in the longwave CO_2 band were analyzed. Example results are showcased in Figure 1 for the shortwave in daytime simulations. They show that the CIRAS-like instrument has good sensitivity; in this example, the temperature profile exhibits around 6 DOFs with average dust loading, and maximum sensitivity between 10 and 25 km of altitude, with a vertical resolution about 3 km in the lowest layer. Performance at night is much less satisfactory, since this spectral range has a significant solar contribution. Simulation of the longwave response is expected to provide similar, or better results to those found on prior instruments operating in this band, e.g., [13].

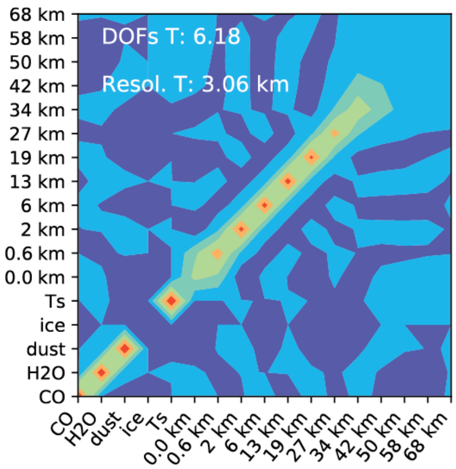

Figure 1: Degrees of Freedom of Signal (DOFS) for a sample tropical location (5°N) on Mars for the shortwave implementation of the HSIR instrument (modeled after CIRAS) during the daytime.

Future Work: Our initial results show that an HSIR sounder has high potential to provide the information we need to improve forecasts on Mars, due both to improved spectral/spatial resolution, and use of new technologies to minimize the instrument footprint and enable more viable flight opportunities. Additional work is ongoing to iterate our retrieval simulations and the instrument design to meet our desired performance. We also plan to advance an Observing System Simulation Experiment (OSSE) framework to demonstrate the impact of a potential future HSIR instrument on Mars forecast accuracy.

Acknowledgments: Part of this work was performed at the Jet Propulsion Laboratory, under a contract with NASA. US Government support acknowledged.

References: [1] Greybush, S.J. et al. (2012) JGR 117. [2] Lee et al. (2011) JGR 116. [3] Lewis, S.R. and P.L. Read (1995) Adv. Space Res. 16, 9-13. [4] Greybush, S.J. et al. (2019), Geosci. Data J. 6, 137-150. [5] Chahine, M.T. et al. (2006) Bull. AMS 87, 911-926. [6] Haberle, R.M. et al. (1993) JGR 98, 3093-3123. [7] Forget, F. et al. (1999) JGR 104, 24,155-24,176. [8] Richardson, M.I. et al. (2007) JGR 112, E09001. [9] Lewis, S.R. et al. (2007) Icarus, 192, 327-347. [10] Santek, D. et al. (2019) Rem. Sens. 11, 2597. [11] Pagano, T.S. et al. (2019) J. App. Rem. Sens. 13(3), 032512. [12] Villanueva, G. L. et al. (2018), JQSRT 217, 86-104. [13] Wolkenberg, P. et al. (2009) JGR 114, E04012.